Low Emittance Electron Gun for XFEL Application

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Abstract. The Paul Scherrer Institute (PSI) in Switzerland is planning to build a cost-effective X-ray Free Electron Laser (XFEL) facility for 0.1-10 nm wavelength and 10-100 fsec pulse length, requiring only 6 GeV electron energy. The facility will consist of a Low Emittance electron Gun (LEG) with high gradient acceleration and advanced accelerator technology for preserving the emittance during acceleration and bunch compression. To demonstrate feasibility of the project, a 4 MeV test stand followed by a new 250 MeV test stand will be used at PSI. An emittance of <0.1 mm-mrad is desired, and this extreme value has prompted the development of several novel features: gated field emitting array, a pulsed high gradient gun, combined photo-field emission, pulsed solenoid focusing and a two-frequency cavity. The LEG should give stable emission of >200 pC, with >700 keV energy and >125 MV/m gradient.

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TEST STAND OVERVIEW

Figure 1 shows the present 4 MeV test stand. The initial acceleration of electrons is across a ~ 4 mm anode-cathode gap. After initial solenoid focusing, the electrons pass through a 2-cell, 1.5 GHz cavity, two further DC solenoids before passing into an emittance monitor. Details of the LEG development are given [1-3].

FIGURE 1. Cross-section of 4 MeV test stand.

The pulsed cathode voltage is generated by an optimized Tesla coil [4]. The shortest possible pulse was wanted to minimize the risk of breakdown, but this was balanced against the need for reasonable lifetime and low jitter for a long development program

of field emitting arrays and photoemission studies. Finally, thyatron switches with a Tesla coil were found to be our best compromise. There is a practical limit to the pulse width possible from a Tesla coil; in our case, ~ 17 secondary turns mean over 20 meters of secondary conductor, and due to speed of light constraints, this limits the FWHM pulse length to the range of ~ 250 ns.

ELECTRODE MEASUREMENTS

Figure 2a shows a rather primitive cathode electrode that was used for earlier tests. It was expected that the unpolished sharp transition from flat to elliptical geometry would give such high field enhancement that breakdown must occur on this circular line. Surprisingly, no breakdowns occurred there, but rather in random locations over the newly machined flat surface. Figure 2b shows one of several surprising features of this surface were found with an electron microscope.

FIGURE 2a. Elliptical copper electrode, 80 mm in diameter, but with the front surface machined flat and not polished.

FIGURE 2b. Enlargement of one breakdown site, image width ~ 100 μm . In the lower part, the copper has been melted. The upper part shows a hardened surface of ~ 1 μm thickness which has peeled back.

Surprisingly, these sharp edges with high β were not sites for later breakdowns.

FIGURE 3. Copper cathode and corresponding copper anode plate, after multiple breakdowns.

Figure 3 shows the results from another rather primitive test, where the anode was flat, but perforated by holes from 1 mm to 6 mm in diameter, and the cathode was a polished copper elliptical electrode. The expectation was that the rather sharp geometry changes around the holes would give preferential breakdown at these sites. Fig.3 shows that most breakdowns (in the 30-40 MV/m range) were not related to the anode holes with right angle edges.

FIGURE 4. Voltage and gradient curves during a typical breakdown test. The gradient started at 30 MV/m and reached 61 MV/m about 45 minutes later before the first breakdown occurred. This event destroys the electrode surface and thereafter the breakdown gradient is around 35 MV/m.

From these results, we have a general knowledge of what is important for controlling breakdown, and that is solely the surface polishing. The following are not dominant in determining breakdown up to 130 MV/m:

- electrode geometry
- material type and purity
- surface scratches
- anode thickness
- argon discharge cleaning
- vacuum pressure
- surface cleanliness
- time in vacuum
- time in service and voltage ramp-up rate

Improving skills in hand polishing gave ever higher breakdown gradients, but also practical difficulties: X-ray emission was completely absent before breakdown so there is no warning of impending breakdown; the first breakdown completely destroys the surface; and to permit uniform polishing, the electrode surfaces should not have a transition from flat to curved geometry on the front surface.

PULSED SOLENOID

A novel feature of the gun is the use of a pulsed focusing solenoid after the initial acceleration, as shown in Fig.5. In this limited space, a DC solenoid would have a limited number of turns, making field asymmetry a problem. To solve this, a pulsed primary solenoid together with a precision stainless steel cylinder as a secondary "winding" was developed.

FIGURE 5a. Cross-section of the LEG, showing location of the pulsed solenoid between AK gap and RF cavity.

The primary and the stainless steel cylinder "secondary" are mounted in a precise ceramic flange, with tolerances in the $\pm 20 \mu\text{m}$ range. The operation is shown in Fig.5b. A pulsed current is applied to the primary for about $150 \mu\text{sec}$; initially, there is a modest circulating

current in the secondary which opposes the change of flux. The primary current is then turned off rapidly; the opposing secondary current is then in the kiloamp current range, and decays with a time constant of $\sim 30 \mu\text{sec}$. During this time, the magnetic field is from the secondary only, and has near-perfect centering and symmetry. Additional advantages of the pulsed solenoid are the zero leakage field at the cathode and low thermal dissipation.

FIGURE 5b. Magnetic field waveforms. Without the secondary, the field is switched rapidly to zero. With the secondary, the field decays with a time constant $\sim 30 \mu\text{s}$.

SUMMARY AND PRESENT STATUS

Over 45 electrode pairs have been tested in the LEG pulser and considerable experience was gained with different materials and surface conditions. Another 40+ pairs are scheduled for testing in the first half of 2009.

Breakdown is presently limited by surface polishing. A gradient of 60 MV/m is standard for most materials, and well polished electrodes could reach 130 MV/m. Stainless steel has become our standard material because of low cost and ease of polishing.

Improvement in surface treatment by electron beam melting and surface deposition is being investigated. Gradients of $>200 \text{ MV/m}$ at 400 kV have been reached but further tests are needed to confirm this result.

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